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On the Design and Deployment of Multitier Heterogeneous and Adaptive Vehicular Networks

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***Abstract*—Research on connected and autonomous vehicles (CAVs) is moving towards first deployments around the world. For complete vehicle autonomy, on top of sensors there is a need for an effective communication system. Due to the critical safety, transmission requirements for these communications are stringent. In an urban environment, with high density of vehicles, standardized dedicated short range communications (DSRC) solely does not perform well. Avoiding costs for new DSRC infrastructure, heterogeneous networks integrating long term evolution (4G-LTE mobile network) and DSRC have shown promising results. With the ever increasing number of vehicles, an optimal integration is required in order to balance the capacity load on the two networks. This paper proposes a systematic approach to designing multitier heterogeneous adaptive vehicular (MHAV) networks. With extensive system level simulations modeling Glasgow city center, incorporating proposed algorithms, scaling of the network along with load balancing between LTE and DSRC have been investigated in this paper. With the design criteria proposed for MHAV, results show that under realistic conditions the probability of end-to-end communication delay to be less than 50 ms is above 90% for a density of 250 vehicles/km^2.**

I. INTRODUCTION

Connected and autonomous vehicles (CAVs) have seen tremendous research efforts in the last decade. The Society of automotive engineers (SAE) have drafted a standard pertaining five levels of vehicle automation [1]. Level-0 (L-0) states no automation where the driver performs full-time dynamic driving tasks. L-1 drive assistance automates either steering or acceleration/deceleration using information about the driving environment. L-2 brings in simultaneous automation in both steering and acceleration/deceleration to provide cruise-control and lane change assistance while the human driver performs all the remaining aspects of dynamic driving. Pure automation starts from L-3, where the driving is performed by automated driving system under controlled environment like straight highways. L-4 advances the automated driving systems to perform all the aspects of dynamic driving under all pre-mapped scenarios. Between L-3 and L-4, the driver is required to respond appropriately (in time) to a request to intervene. Finally, L-5 states full automation, where the presence of steering, accelerator, brakes, etc. are not required in the vehicle.

Automation up until L-3 and some driving modes of L-4 is achievable using sensors or cameras on board the vehicle. However, according to [2]–[4], L-4 and above automation requires an efficient vehicular communication network. These communications pertaining CAVs are also a big part of co-operative intelligent transportation systems (C-ITS) where, human safety is vital among other applications. Exchange of information is carried out in the form of vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), all collectively termed vehicle-to-everything (V2X) communications. Essential communications for vehicle safety at L-4 and above automation requires the use of heterogeneous networks [4]. These are multi-radio networks integrating dedicated short range communications (DSRC) and mobile networks such as long term evolution (LTE), evolving the 4G and 5G technologies. A number of LTE performance evaluations for the feasibility of use with vehicular ad hoc networks (VANETs) have suggested significant suitability, however, without any centralization; VANETs can pose enormous network capacity issues on the cellular network [5]. With the global mobile data traffic increasing sevenfold between 2016 and 2021 [6], the availability of spectrum for VANETs can be uncertain.

In terms of using only DSRC for vehicular communications, low latency is experienced as compared to LTE, however, a new infrastructure is required for V2I communications. Successful message delivery in highly dense urban scenarios is also not evident [7]. For the centralization of DSRC, there are some proposed techniques and frameworks. Among these, clustering and various routing protocols [8] are some of the promising DSRC techniques. However, with clustering or direct vehicular communication, the concern of privacy and security arises.

For the purpose of VANET centralization on LTE, group formation, multicast/broadcast management system (MBMS) and device-to-device (D2D) communications have been proposed [9], [10]. Group formation also known as clustering has shown promising performance. However, according to [11], 35% of road users are concerned about privacy in regards to sharing their information with other road users. At the same time, clustering relies on relaying transmissions which can pose a privacy and security issue [12]. MBMS functionality also proved to be reliable for message dissemination, although being part of 3GPP specifications, MBMS is not widely implemented by mobile network operators (MNOs) [13]. Similarly, D2D communications also referred to as LTE direct communications, using full duplex radios in order to enable vehicles to receive and transmit at the same time, have shown reduction in the use of LTE uplink resources, increasing network capacity. However, D2D for VANETs exhibits an increase in interference [10] and similar to MBMS, is not currently implemented by MNOs.

Due to the frequent and fixed routes of public transit, studies have suggested the use of buses as mobile gateways (MG) instead of fixed road-side units (RSUs) [14]–[17]. Many advantages such as their tall structure exhibiting higher transmission range, covering most parts of urban areas, no requirement of privacy mechanisms and avoiding the cost of installing a new infrastructure, make public buses a good substitute for fixed base stations. This paper builds upon our previous work that proposes a multitier framework [18], where authority owned or public transport are high tier nodes (HTN) acting as MGs, incorporating message dissemination scheme proposed in [19] with a fallback mechanism and MG registration technique proposed in [20].

With the technical aspects of the proposed architecture including efficient message forwarding, robust registration scheme and reliable fall back mechanism in place, this paper includes a systematic approach to the design and deployment of multitier heterogeneous adaptive VANETs (MHAV) in urban environments is proposed. Contributions of this paper include:

- Design criteria for a multitier heterogeneous and adaptive vehicular network (MHAV).
- Performance evaluation of MHAV under realistic urban environment with high density of vehicles employing mutlicell and multipath channel fading models.

The remainder of this paper is organized as follows: Section II describes the design criteria for multitier heterogeneous framework, and Section III elaborates on the system model followed by simulation results in Section IV. Conclusions and future work are then discussed within Section V.

II. Multitier Heterogeneous Adaptive VANETs

The proposed multitier heterogeneous adaptive VANET (MHAV) framework incorporates high tier nodes (HTN) and low tier nodes (LTN). HTNs are the authority owned vehicles such as public buses, taxis, council lorries, etc. while LTNs comprise all the other private vehicles. Both HTNs and LTNs are assumed to be equipped with LTE and DSRC interface, integrated with the help of a control device.

Data delivery in the proposed framework is carried out with the cooperation of HTNs, traffic control center (TCC) and vehicular safety application (VSA) server. The TCC and VSA are situated at the core of mobile network. All the LTNs get registered with HTNs, which then enables V2I communications. If an HTN is not available, LTN falls back to using LTE network. HTNs consistently communicate with the LTE network, updating the traffic conditions and their registered LTNs table with the TCC and VSA. HTNs broadcast beacons every second consisting of their location, velocity and ID using DSRC. LTNs receiving these broadcasts run the registration algorithm in order to register with the most suitable HTN. Once the LTN is registered, all V2V communications are carried out via the registered HTN, acting as a message relay. The basic architecture of MHAV framework is shown in Fig. 1.

Since all the traffic related information is updated in the TCC, LTNs not registered with HTNs can also access this information via the mobile network. In regards to safety applications, we suggest the use of a differentiated quality of service (QoS) mechanism known as safety application identifier (SAI) proposed in [19] and implemented via the VSA server. In the next subsection, the multi-radio access technology (RAT) network is elaborated followed by the HTN selection algorithm which is implemented at the LTN. Furthermore, MHAV framework has a number of benefits over other previous similar approaches such as no clustering requirement, more efficient adaptation, higher applicability, increased security, better network load balancing, etc.

A. Multitier Multi-RAT Network

The proposed network is multitiered in terms of high and low tier nodes, however, the radio technologies employed are integrated and assumed to be present in all vehicles. DSRC operating at the 5.9 GHz band with carrier sense multiple access with collision avoidance (CSMA/CA) faces difficulties when it comes to highly dense urban areas. DSRC frequency band is also found not to be suitable for NLOS conditions at intersections due to buildings and foliage [21]. On the other hand, LTE operating at lower frequency bands than DSRC, is found to be suitable for vehicular communications. However, due to scalability and capacity issues, mobile networks with an ever increasing number of users, might not be able to accommodate the vehicular networks. As mentioned earlier, vehicle safety have stringent requirements in terms of latency. Therefore, need for a multi-RAT system, overcoming shortfalls of independent RAT, is in place.

The most important requirement is the latency of message delivery. For a human driver, the stopping distance for when a hazard happens is the sum of driver thinking distance and actual braking distance [22]. The thinking distance is the time for a driver to react to a situation. For an autonomous vehicle, message must be delivered during the thinking distance time, in order to prevent an accident. For a vehicle driving at 30 miles per hour, stopping distance is 23 m where 9 m is the thinking distance and the remaining 14 m is the actual braking distance. Keeping this in mind for urban environments, using the time, distance and speed relationship, the time an autonomous car will have to make a decision would be less than 670 ms. However, if the speed increases, the breaking distance increases while decreasing the thinking time.

Apart from these driving rules, the standards require a latency of less than 100 ms [23] while literature has benchmarked it at 50 ms for successful implementation of vehicular networks [24], [25]. With these driving rules and the standard requirements, a suitable RAT is to be determined. For our proposed framework, we find DSRC to be effective in the low tier, however, with no presence of HTN, latency requirement can also be met by LTNs communicating over LTE, provided the mobile network is not saturated.

B. HTN Selection Algorithm

By having HTNs with integrated DSRC and LTE, a system is designed where the HTNs act as gateways and message relays. In order to choose an HTN, LTNs run our proposed algorithm every time a broadcast beacon is received. Similar to the scheme proposed in [14], each HTN maintains a registration table recording the LTNs currently registered with them. These tables are constantly reported and updated by TCC over the LTE network. In order to have a robust network, especially with such a mobile topology, determining which HTN to select for registration is an important issue when LTNs can receive multiple broadcast beacons from a number of HTNs.

When an LTN receives a broadcast beacon from HTN, this node is placed in the candidate registration set (S). Using the information in the broadcasted beacon, LTN calculates the connection delivery delay (T) for every HTN in the

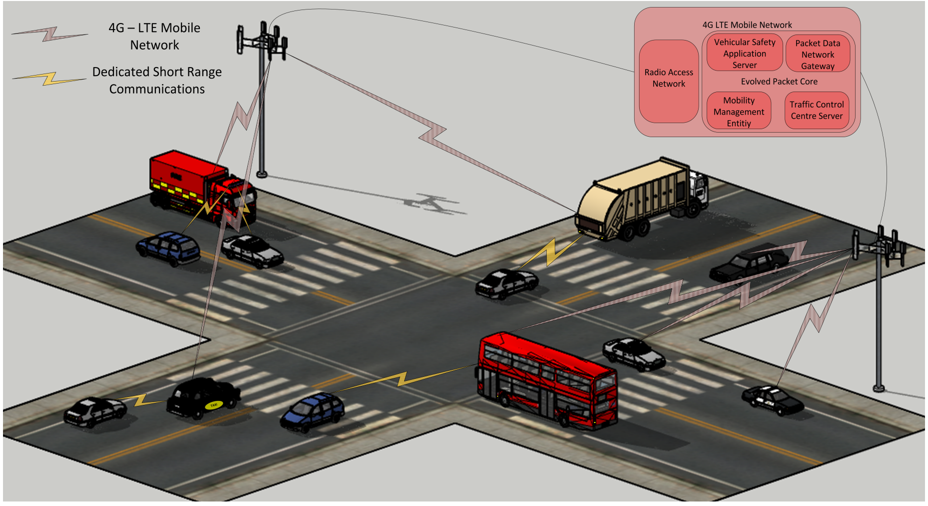


Fig. 1. Multitier Heterogeneous Adaptive VANET Framework showing HTNs and LTNs with possible scenarios.

candidate registration set. This delay is calculated using HTN's predefined transmission range (R), distance between the HTN$_j$ and LTN$_i$ (d_{ij}) and their relative velocity ($v_i - v_j$). Negative value of this delay means that the HTN is moving in the opposite direction to the LTN, therefore if T is negative the HTN is placed in the discard set. Out of all the HTNs residing in S, the one with the highest T is selected for registration. Once LTN has registered with the HTN, it stays connected with it while the distance between LTN and HTN remains below R. Proposed registration algorithm is elaborated in [20].

Setting a threshold and employing multi-hop approach avoids ping-pong effect but results in high delays [14]. To tackle this ping-pong problem in our evaluations, we preset R and force the LTN to stay connected with the registered HTN until it moves out of the transmission range. To select an optimum R, the system is tested under varying values of R. The results showed a trade-off between number of registration switches and DSRC coverage area for urban environment. Once the LTN is aware of its forwarding via the chosen HTN, message dissemination can be carried out accordingly. Different aspects and scenarios for message dissemination are discussed in the following subsection.

C. Message Dissemination Scenarios and Network Scalability

Successful message delivery is vital for vehicular safety applications, hence, the designed framework must maintain connectivity at all times. Network scalability and redundancy play a vital role along with robust adaptive message dissemination schemes. In terms of network scalability and message dissemination, VSA server placement near the edge of the network is necessary. Considering the data freshness concept, ideal location of the server would be at the EPC. Therefore, having multiple EPCs serving their respective geographical locations would have their own VSA servers with a similar approach as is for mobility management entity (MME), reducing the RTT while increasing the system capacity and eventually meeting the strict transmission requirements for vehicular safety applications [26].

Recent 3GPP release 15, outlining 5G mobile networks, proposes network slicing in order to make the network flexible and scalable [27]. 5G is considered to be an evolution of LTE, where rel-15 currently specifies the migration procedures to 5G. Network slicing deals with the scalability problem specially for vehicular communications over mobile networks. Initial concept for network slicing proposes virtualization of networks serving dedicated applications such as vehicular networks, mobile broadband, voice and video applications, and so on. For the remaining of the paper, results and discussions are included with respect to the following scenarios in an urban environment.

1) Scenario-I: HTN - DSRC Message Dissemination: As mentioned earlier, V2V communications take place via the selected HTN. This type of communication employs DSRC to enable low latency message forwarding. Once an LTN$_i$ is registered with an HTN$_x$, it will start sending periodic messages to the HTN$_x$. This HTN will then look up the routing tables and determine the forwarding set as:

$$\mathbf{F}_i = \{\forall k : d_{ik} < R_i, i \neq k\}, \tag{1}$$

where R_i is the awareness range, d_{ik} is the distance from LTN$_i$ to the neighboring LTN$_k$. Recalling the concept of safety application indexing [19], depending on the application, the HTN$_x$ will adapt to the respective R_i and beacon frequency for the particular message type sent by the LTN$_i$. In the case, where a receiving LTN$_k$ is registered with another HTN$_y$, the tables populated and updated by TCC are looked up to determine whether the HTN$_y$ is in the transmission range of HTN$_x$. If the latter is not in the transmission range, then the mobile network along with TCC server forwards the message to the respective HTN.

2) Scenario-II: HTNs Offloading LTE: Having HTNs serve LTN communications, addresses the privacy issue while providing low latency communications and balancing the load on the two radio networks. In this scenario, we simulate the entire network while evaluating the performance and load on LTE network. For designing purposes, we determine the ratio of HTNs to LTNs in order to provide efficient safety communications. With this ratio, load balancing between DSRC and LTE is evaluated.

3) Scenario-III: LTE Message Dissemination: If an HTN does not fulfill the criteria described in [20], it will result in the LTN being disconnected from the DSRC network. To ensure full time connectivity we propose a fall-back to using the LTE mobile network. Previous evaluations show that the LTE

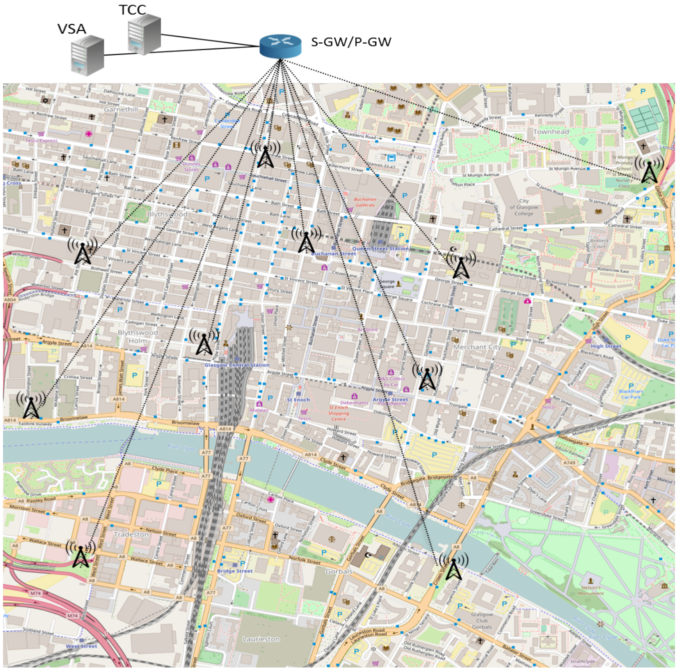


Fig. 2. 2x2 km^2 area of Glasgow city center covered by 10 sites with 3 cells/site.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Simulation time	300 seconds.
Road model	2x2 km^2 Glasgow City Center
Number of LTNs	1000, 2000 vehicles/km^2.
Ratio of HTNs to LTNs	0, $\frac{1}{10}$, $\frac{3}{10}$, $\frac{5}{10}$.
Average speed	20 mph (HTN), 30 mph (LTN).
DSRC	
Access Technology	IEEE 802.11p.
Propagation model	Nakagami-m and Log distance Models.
Operating Frequency	5.9 GHz.
Data Rate	6 Mbps.
Transmission Power	25 dBm.
Antenna	Omnidirectional.
Channel Bandwidth	10 MHz.
Noise Figure	7 dB.
CCA threshold	-86 dBm.
LTE	
Network	10 sites with 3 cells/site.
Transmission power	eNB: 40 dBm, UE: 23 dBm.
Carrier frequency DL/UL	2115 MHz/1715 MHz.
Channel bandwidth	20 MHz (100 RBs)
Noise Figure	eNB: 5 dB, UE: 9 dB.
UE antenna model	Isotropic (0 dBi).
eNB antenna model	15 dB Cosine model, 65^o HPBW.
Scheduling algorithm	Proportional Fair.
Handover algorithm	A2A4RSRQ, RSRQ threshold -5 dB, and NeighbourCellOffset=2 (1 dB).
Path loss model	LogDistance ($\alpha = 3$) and 3GPP Extended Vehicular A model.

network can accommodate a low density of vehicles provided a resource allocation scheme is in place [26]. Therefore, in a high density network, if a certain ratio of LTNs are offloaded to DSRC, the LTE mobile network can substantially meet the transmission requirements. This is further explained in Section IV.

III. SYSTEM MODEL

The network modeled is a 2x2 km^2 area of Glasgow city center with varying density of vehicles evaluating both rush hours when there is high presence of HTNs and less busy hours with less HTNs available. Both LTNs and HTNs are assumed to be equipped with FDD LTE transceivers with 20 MHz bandwidth, uplink carrier frequency 1715 MHz and downlink carrier frequency 2115 MHz (band 4) [28, Table 5.5-1] integrated with IEEE 802.11p compliant DSRC interface operating at 5.9 GHz with 10 MHz bandwidth. These nodes are assumed to be moving in urban model created using routes mobility model [29]. Fig. 2 illustrates the service area modeled in ns-3 [30]. Nodes move at an urban average speed matched to the 3GPP extended vehicular A (EVA) model radio environment designed using MATLAB [31]. Simulation parameters used are given in Table I.

Furthermore for HTNs, predefined bus routes are modeled with an interval of 10 minutes. For the eNodeBs (eNBs), mast data for operator EE has been implemented. The eNBs are connected to the mobility management entity (MME) through their S1-AP interface and to the serving gateway (S-GW) and packet data network gateway (P-GW) through their S1-U interfaces. Interconnection from the P-GW to the TCC Server and VSA server is modeled using an error free 10 Gbps point-to-point link and TCP/IP version 4. The packet payload for HTNs is assumed to be 1500 bytes including the registration tables, locations and safety application data.

Propagation loss model employed for IEEE 802.11p is Nakagami loss model with the path loss factor (m) of 4 on top of Friis propagation loss model. Results are obtained by scaling the modeled network. An area of $200 \times 200\,\mathrm{m}^2$ is first modeled with 10 vehicles, then the network is scaled with a linear scale factor (SF) of 2 and 3 to areas of $400 \times 400\,\mathrm{m}^2$ and $600 \times 600\,\mathrm{m}^2$ with 40 and 90 vehicles respectively. Simulation performance results for previously used $2 \times 2\,\mathrm{km}^2$ model with 200 vehicles (50 vehicles/km^2) [18] suggest that provided the LTE network coverage is the same as $600 \times 600\,\mathrm{m}^2$ area, performance of 250 vehicles/km^2 can be evaluated in an area of $2 \times 2\,\mathrm{km}^2$ considering the performance degradation observed in the scaled areas. LTN velocity is set to 30 mph while the HTNs are assumed to be moving at 20 mph, according to the city speed limits enforced in Glasgow city center.

We compare our scenario-I results with the previously proposed longest registration time algorithm implemented for traditional BUS-VANETs [14]. The primary performance measure used is the *end-to-end message delivery delay*. For scenarios-II and III, we evaluate the capacity of LTE network in terms of successful message delivery within the latency requirement set forth by standards and previous works.

IV. SIMULATION RESULTS

Vehicular networks have a fast changing topology due to their mobile nature. In the proposed MHAV framework, LTNs carry out V2V communications via HTNs. Therefore, the evaluation of experienced latency over such an architecture is vital. We first compare our message dissemination scheme employed by HTNs with the traditional BUS-VANET where the HTNs act merely as road side units (RSUs). Fig. 3 shows the cumulative density function (CDF) for the end-to-end delay for the scenario-I described in Section II-C1. Probability of message dissemination delay between LTNs via HTNs to be less than or equal to 50 ms is above 90% for the proposed scheme.

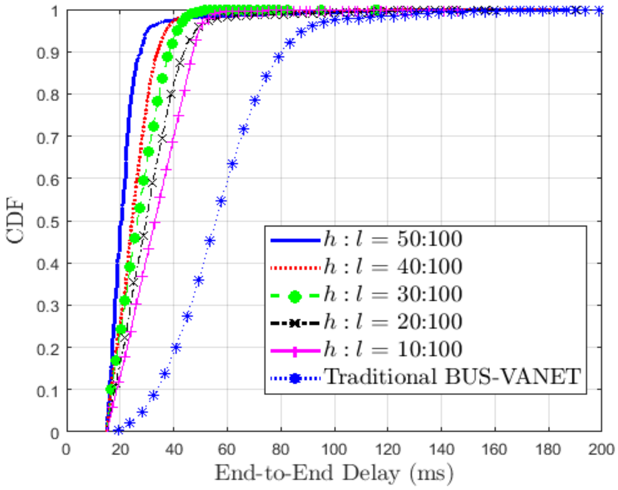
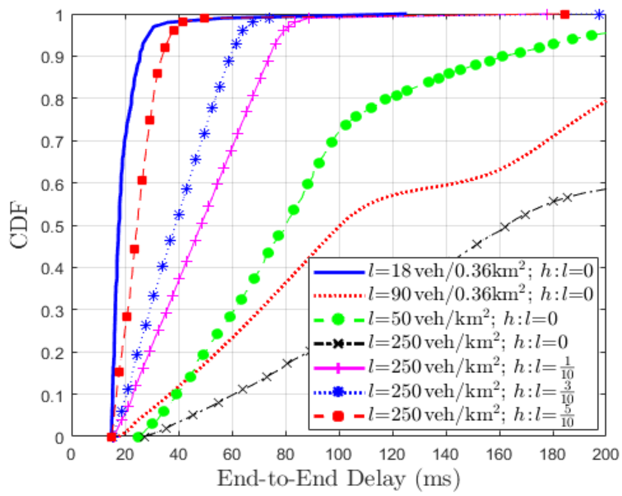
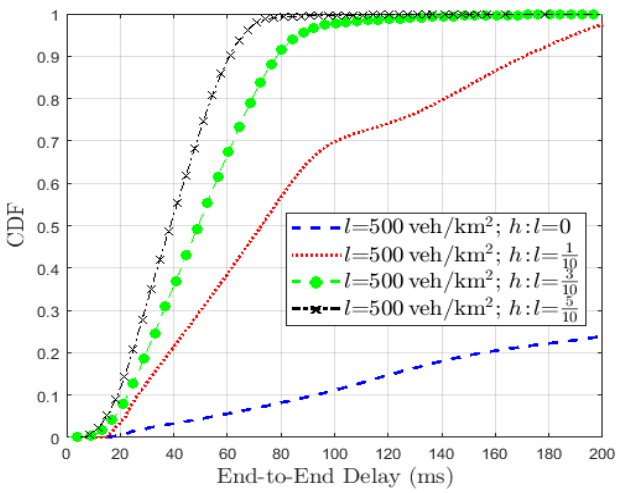


Fig. 3. Scenario-I: HTN - LTN Message Dissemination End-to-End Delay



(a)



(b)

Fig. 4. Scenario-II & III: LTE End-to-End Delay in $2 \times 2\,\text{km}^2$ Glasgow City Center MHAV Framework (a) For 250 LTNs/km^2, (b) For 500 LTNs/km^2.

Comparing with the traditional BUS-VANET, a gain of about 50% is observed in the probability of end-to-end delay being $\leq$ 50 ms. It can also be observed, that increasing the number of HTNs, performance improves. With 10 HTNs for 100 LTNs, this probability of end-to-end delay being $\leq$ 50 ms is 90%. While increasing the number of HTNs to 50 for 100 LTNs, an increment of 8% can be observed. The reason for better performance is the resource utilization criteria, restricting the transmission area to the required awareness range. This approach leads to less capacity blocks and eventually lower broadcast flooding. Traditional BUS-VANETs propose performance improvements by adding RSUs in the network. While we propose to incorporate authority owned vehicles, which include public buses, council lorries, taxis, police patrolling cars, etc in MHAV architecture. This increases the number of HTNs, hence improving the network performance.

Furthermore, traditional BUS-VANETs face more delays due to the frequent switching between HTNs due to their proposed longest registration time algorithm. The amount of registration switching between HTNs is required to be low for the network to be robust and low latent. We tackle this problem in the registration criteria, which enables the HTN to reject registration in case of overloading and determine the highest connection delivery delay (T) respectively.

Next we analyze scenarios II and III, where LTNs are either offloaded on to HTNs or if the HTN is not available, LTNs communicate via the LTE mobile network. Fig. 4 shows the CDF for end-to-end delay in $2{\times}2\,\text{km}^2$ Glasgow city center employing the proposed MHAV framework. In order to establish a design criteria, a highly dense urban environment is investigated. Densities where the network gets heavily loaded are evaluated, while increasing the number of HTNs to satisfy the end-to-end delay requirement.

Fig. 4a shows the CDF of end-to-end delay experienced by 18 and 90 vehicles in $600{\times}600\,\text{m}^2$ along with 200 vehicles in an area of $2{\times}2\,\text{km}^2$ (50 veh/km^2). With the system degradation observed for increasing density of 18 to 90 veh/0.36km^2, results for 1000 LTNs (250 veh/km^2) are obtained. For the case where there is no HTN present, the network with 250 veh/km^2 is observed to be choked with probability of end-to-end delay being $\leq$ 50 ms at less than 10%. However, when there is 1 HTN for every 10 LTNs present in the network, this probability goes up by 40%. Furthermore, it can also be observed that by increasing the number of HTNs, the performance in term of latency improves. With 5 HTNs for every 10 LTNs in the network, the probability of end-to-end delay being $\leq$ 50 ms further improves to 98%.

As expected, increasing the density of vehicles in the network leads to further performance degradation. Fig. 4b shows the end-to-end delay probability for a density of 500 vehicles/km^2. It is seen that with no HTN present, the end-to-end delay probability of less than 50 ms is only 6%. Even with HTN to LTN ratio of 1:10, the network does not accommodate vehicular communications. However, with this ratio at 5:10, the probability for delay to be $\leq$ 50 ms is around 75%. Therefore, it can be deduced that even with centralization and use of heterogeneous networks, high density networks pose capacity problems. Nevertheless, for a density of 250 vehicles/km^2, the proposed framework outperforms traditional vehicular networks.

V. Conclusion and Future Work

This paper proposes a systematic approach for designing a multitier heterogeneous adaptive VANET (MHAV) framework which consists of HTNs and LTNs. All the vehicles are assumed to have LTE and DSRC capabilities while LTNs register with HTNs to enable V2I and V2V communications over DSRC while the HTNs connect to the LTE network in order to provide infrastructure communications to its registered LTNs. A fall-back to LTE SAI in the case where there's no HTN present for registration is also proposed. Having authority owned HTN gateways tend to make the network more secure and addresses the privacy issue raised by many private car owners. Extensive system level simulations are carried out in Glasgow city center, a dense urban environment, in order to evaluate our proposed scheme. Results show that the proposed framework outperforms the traditional BUS VANET by almost 50% in terms of probability of end-to-end delay being $\leq$ 50 ms.

We also evaluate a scaled up model of $2{\times}2\,\text{km}^2$ with 1000 LTNs communicating via either HTNs or LTE mobile network. Gain of about 40% in terms of delay probability being $\leq$ 50 ms is observed when the HTN to LTN ratio is 1:10. This 50 ms delay probability is further improved to 98% with the HTN to LTN ratio of 5:10. Therefore, having heterogeneous networks incorporating our proposed multitier framework improves system performance in terms of latency, eventually paving way for L-5 vehicle automation.

In the future, we plan to investigate highway scenarios with MHAV, where due to the less frequent change in topology, certain parameters in our proposed scheme are speculated to be significant. LTE has been a promising candidate for vehicular networks. However, with the current growth in mobile users, catering for vehicular networks would require much more capacity. We also plan to investigate the impact of network slicing at 5G core for improving scalability and flexibility in vehicular networks.

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